The Virtual Planetary Laboratory

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Universidad Nacional Autonoma de Mexico
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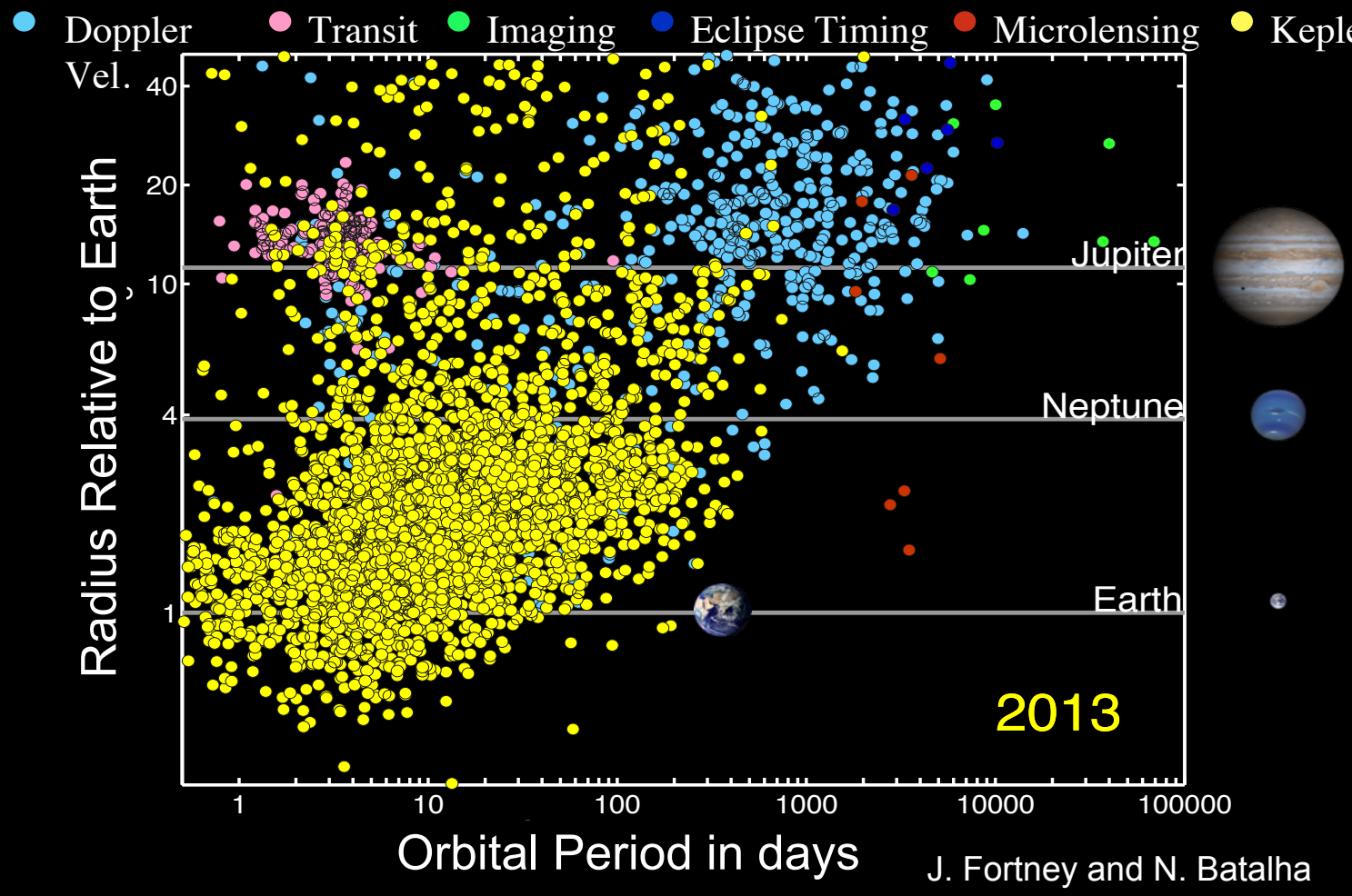
NASA Goddard Space Flight Center
Pacific Science Center
Pennsylvania State University
Princeton University
Rice University
San Jose State University
SETI Institute
Space Telescope Science Institute
Stanford University
University of Victoria
Washington University in St. Louis
Weber State University
Yale University

VPL's Scientific Question

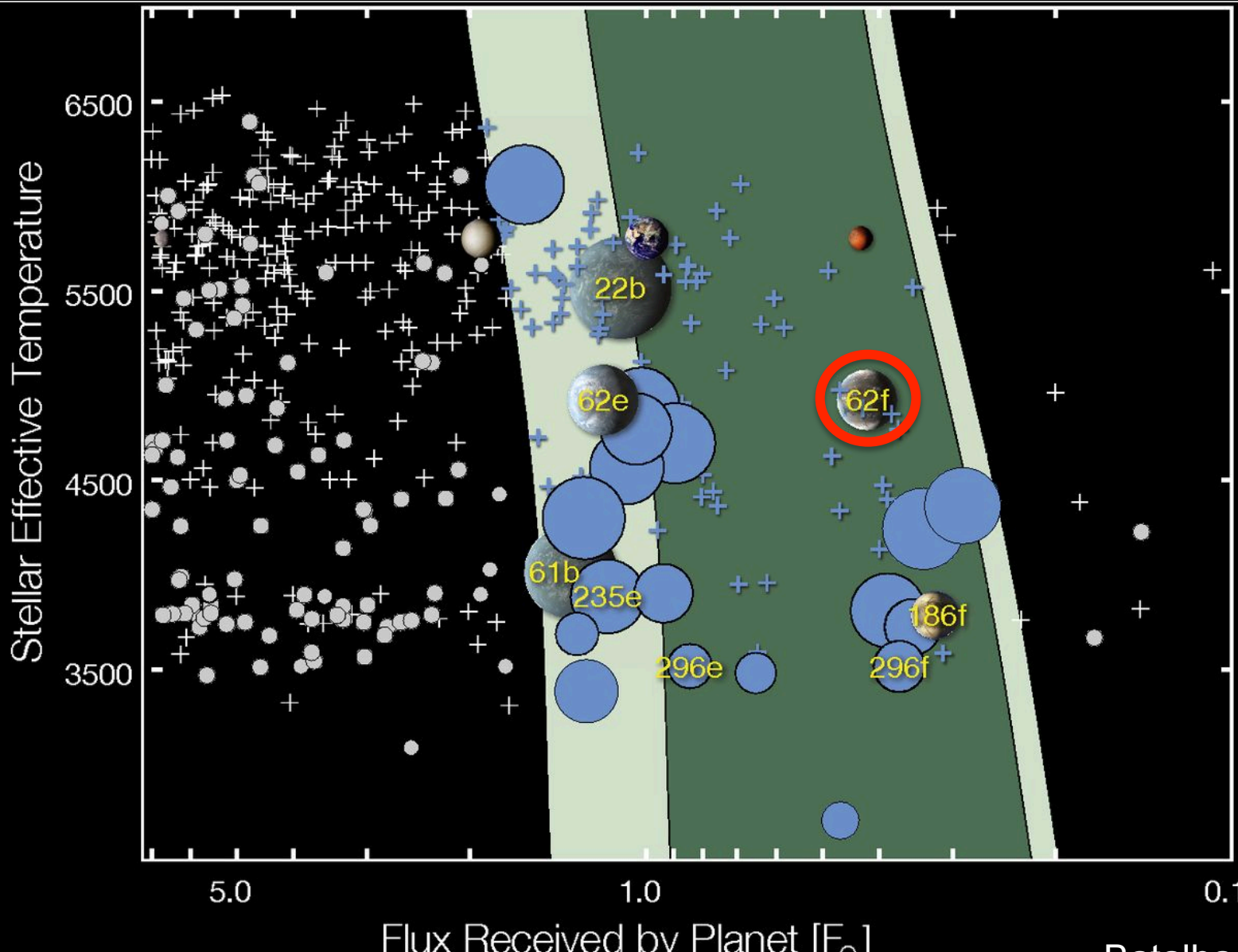
How would we recognize whether an extrasolar planet can or does support life?

Planets, planets, everywhere…



As of this morning….
1849 Planets, 1160 planetary systems, 471 multi-planet systems

Companions for Earth



Batalha, 2014

NASA's UV, Visual, & IR Astrophysics Facilities

AFTA

JWST

Kepler

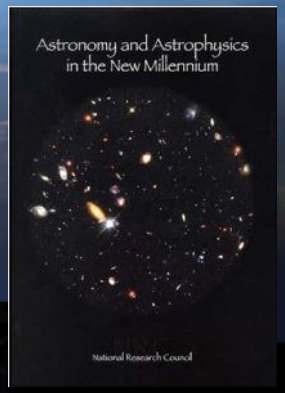
Observatory for the 2020s

Spitzer

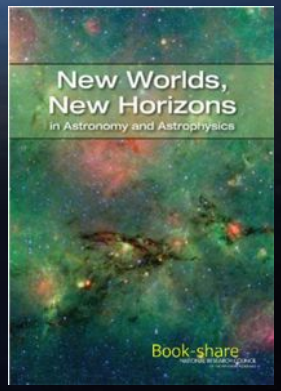
Hubble

Ground-based Observatories

2001 Decadal Survey



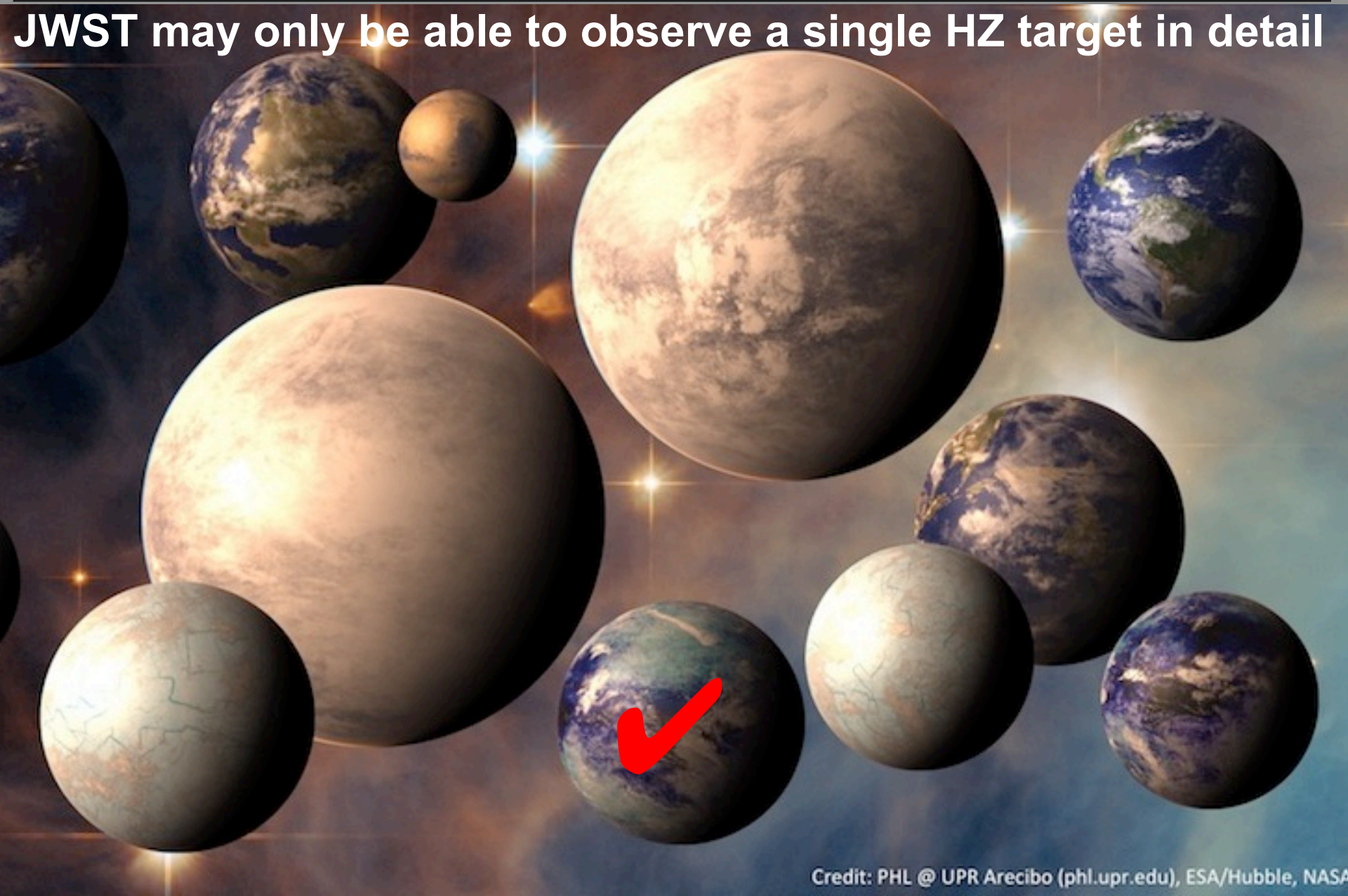
2010 Decadal Survey



Adapted from Testimony to Congress Given by J. Grunsfeld (May 5, 2013)

Target Selection via Comparative Habitability

JWST may only be able to observe a single HZ target in detail

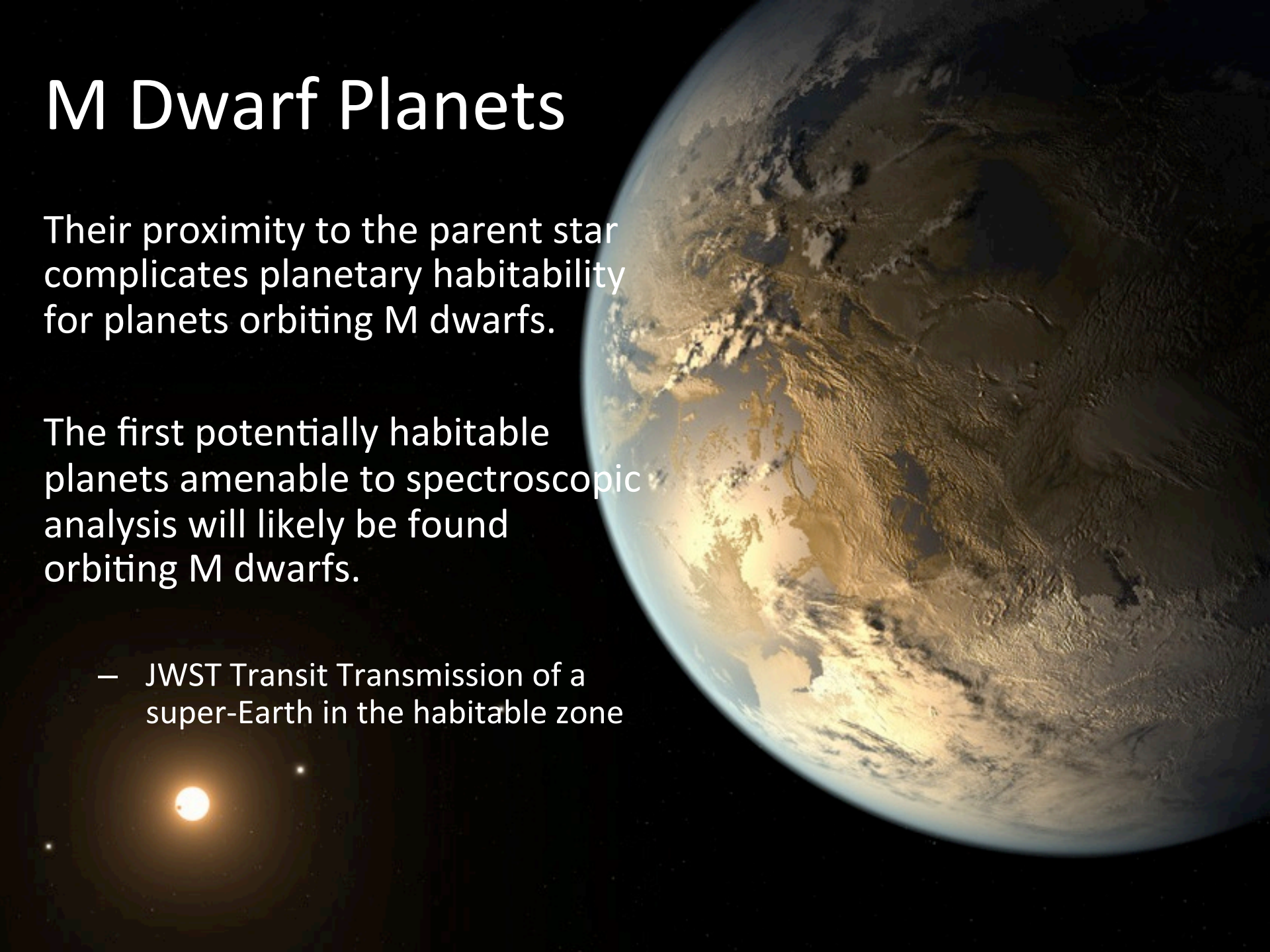


M Dwarf Planets

Their proximity to the parent star complicates planetary habitability for planets orbiting M dwarfs.

The first potentially habitable planets amenable to spectroscopic analysis will likely be found orbiting M dwarfs.

- JWST Transit Transmission of a super-Earth in the habitable zone



VPL Mission-Relevant Goals

Enhance the science return from the Kepler mission

- providing the fundamental research, and the suite of modeling tools required to make an interdisciplinary assessment of the habitability of Kepler planets, consistent with the known observational data.

Provide the tools and interdisciplinary expertise to assess and rank the habitability of targets for JWST

- and to maximize information retrieval from the spectra that are obtained.

Inform the downselect and maximize the science return from direct imaging planet detection and characterization missions

- modeling plausible extrasolar planetary environments and determining the detectability and measurement requirements for signs of habitability and life on extrasolar planets.

Challenges to Characterization

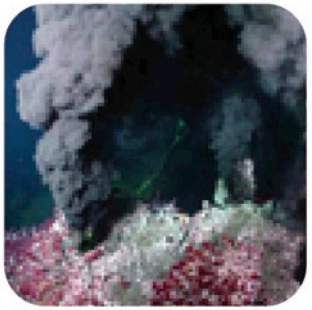
The Virtual Planetary Laboratory

Earth as an Exoplanet

Earth Observations
GCM Results

The Earth Through Time

Field Work
Lab Studies
Computer Models



The Habitable Planet

Planet Formation
1-D/3-D Climate/Chemistry
Orbital Dynamics
Stellar Observations

The Living Planet

Field Work
Lab Studies
Computer Models

Observer

Products

Validation

Disk-averaged spectra over a full year for Earth and other planets

Environmental constraints

Climate, Biosignatures

Disk-averaged spectra at several stages of evolution

Habitability assessment

Disk-averaged spectra

Climate and limits of the habitable zone for plausible extrasolar planets

Limits of photosynthesis

Impact of life on planetary environments

New biosignatures

NASA Astrobiology Institute

PI: Victoria Meadows

Project Administrator

Task A:
Earth as an Extrasolar Planet

- *Robinson*
- *Meadows*
- Crisp
- Sparks

1 graduate student
0.5 postdoc

Task B:
The Earth Through Time

- *Domagal-Goldman*
- *Baross*
- Bolton
- Buick
- Catling
- Claire
- Conrad
- DesMarais
- Goldblatt
- Hoehler
- Kasting
- Meadows
- Pierrehumbert
- Robinson
- Sleep
- Zahnle

3.5 graduate students
(UW, PSU)

Task C:
The Habitable Planet

- *Barnes*
- *Kasting*
- Armstrong
- Bitz
- Crisp
- Domagal-Goldman
- Goldblatt
- Hawley
- Kress
- Meadows
- Pierrehumbert
- Quinn
- Raymond
- Segura
- Sleep
- Walkowicz
- Yung
- Zahnle

4.5 graduate students
(UW, U. Chicago)
1 postdoc

Task D:
The Living Planet

- *Kiang*
- *Hoehler*
- Blankenship
- Catling
- Claire
- Conrad
- Domegal-Goldman
- Meadows
- Parenteau
- Siefert

2 graduate students
(UW)

Task E:
The Observer

- *Meadows*
- *Crisp*
- Agol
- Brown
- Deming
- Robinson

2.5 graduate students
(UW, UMD)
0.5 postdoc

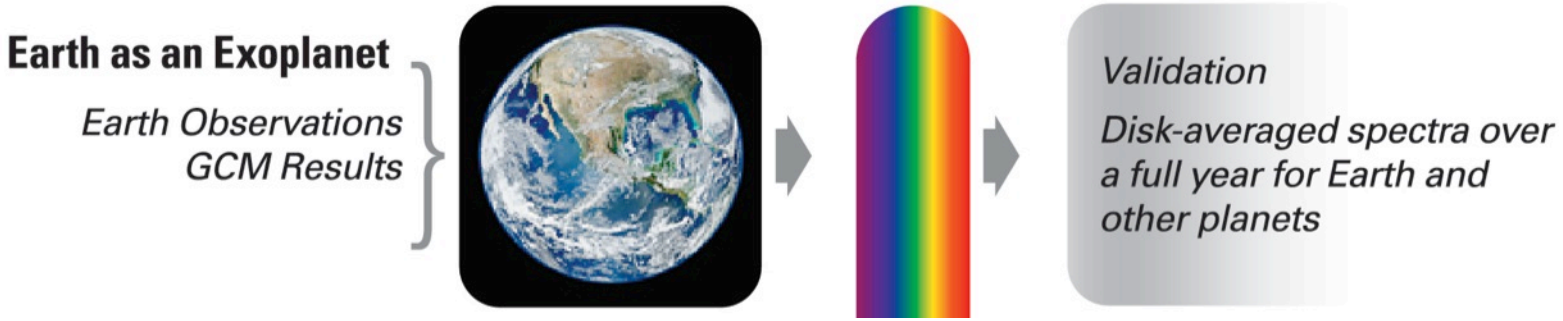
E/PO

- Harnett
- Meadows
- Barnes
- Conrad
- Crisp
- Domagal-Goldman
- Hoehler
- Kiang
- Kress
- Robinson
- Segura
- Siefert
- Walkowicz

0.5 graduate students

- Astronomy
- Dynamics
- Biology
- Geology
- Atmospheric Chemistry
- Climate Modeling
- Spectroscopy
- Instrumentation
- Earth Science
- EPO Specialty

Multidisciplinary = fruit salad
Interdisciplinary = fruit smoothie
- M. Voytek



Objective 1: Characterize Habitability and Biosignatures for an Earth-like Planet.

Produce a definitive dataset of the photometric and spectral characteristics for the Earth

Upgrade the model to:

- **Support transit transmission simulations**
- **Add polarization capability (in collaboration with the OCO-2 Team),**
- **read in 3-D GCM data.**

Products are used to:

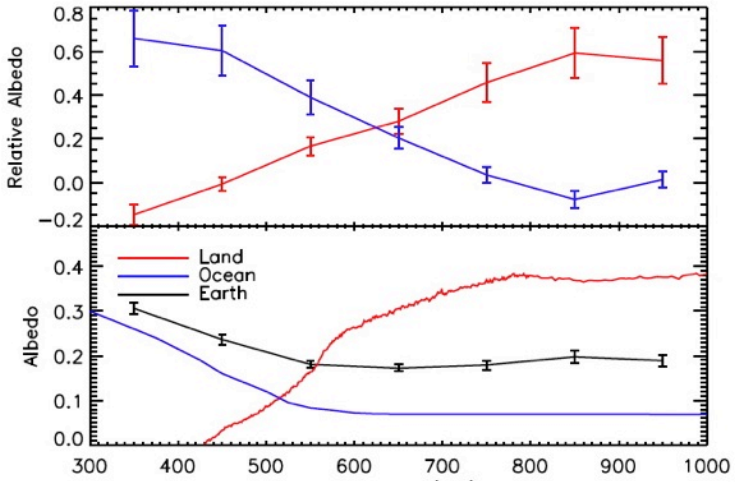
- **explore the detectability of signs of habitability and life for the Earth**
- **validate the retrieval techniques developed in Task E: The Observer, and**
- **expand our 3-D spectral visualization capability to planets other than the Earth.**

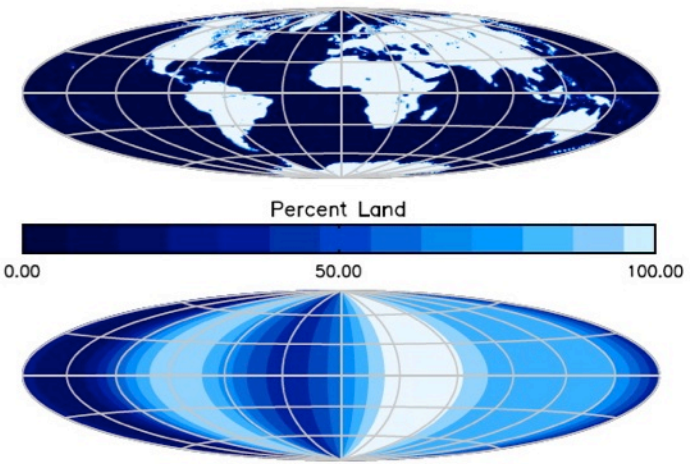
Earth as an Exoplanet

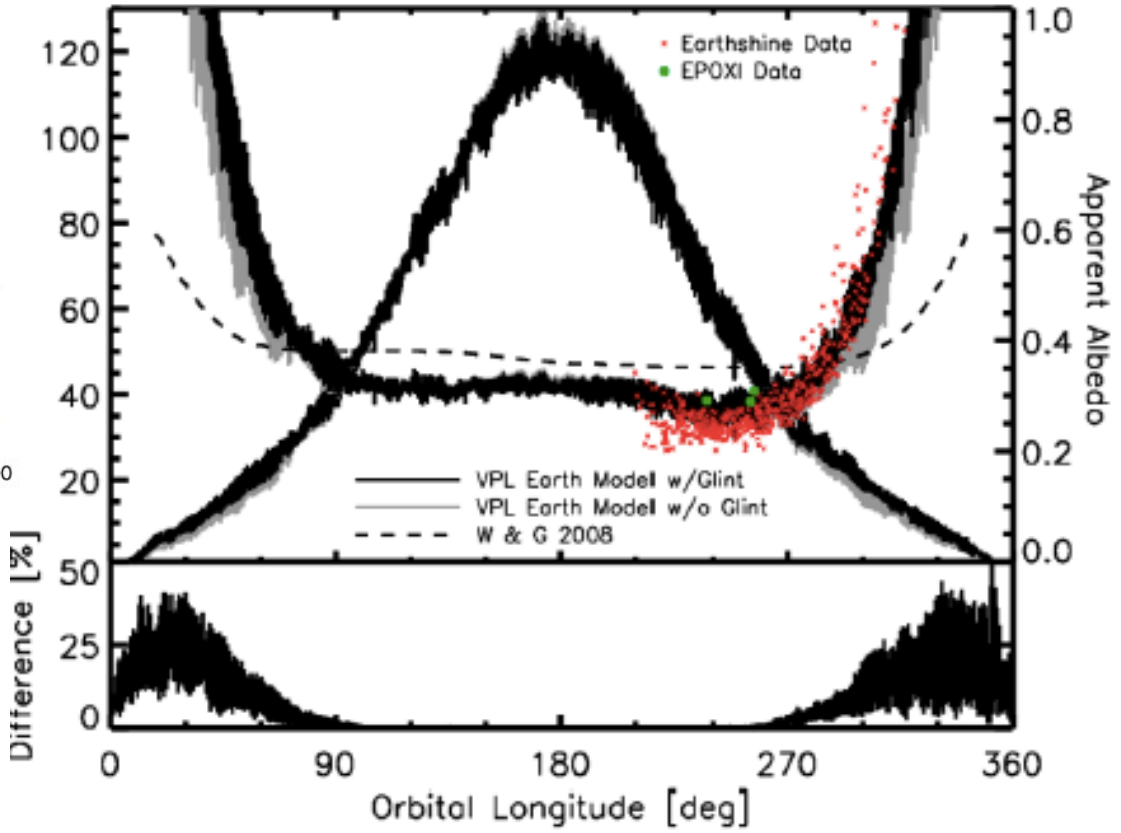
Earth Observations
GCM Results

Validation

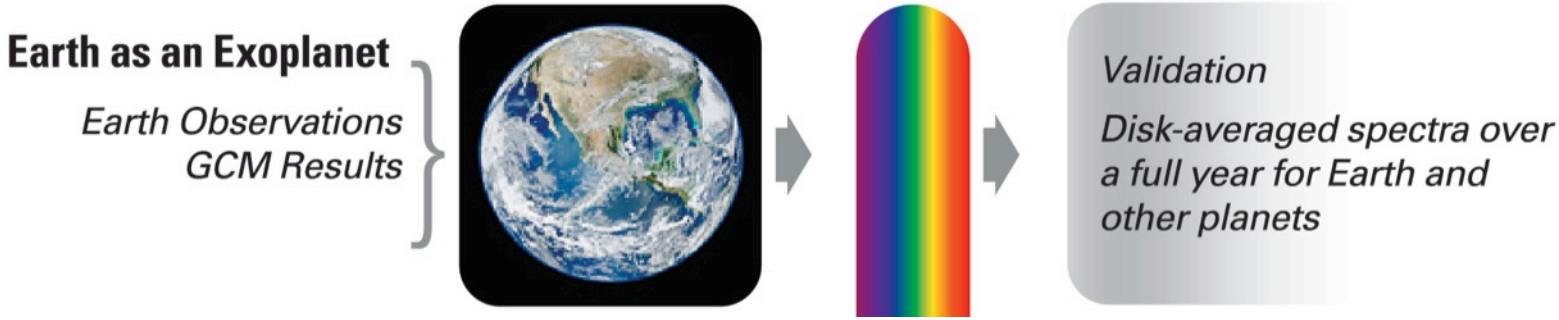
Disk-averaged spectra over a full year for Earth and other planets

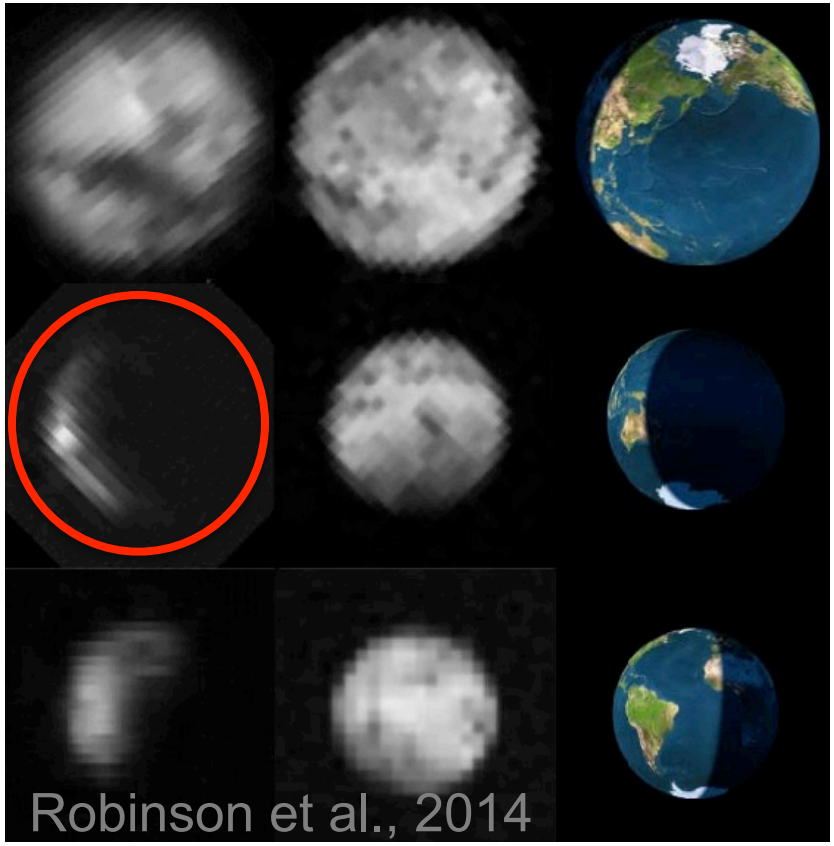


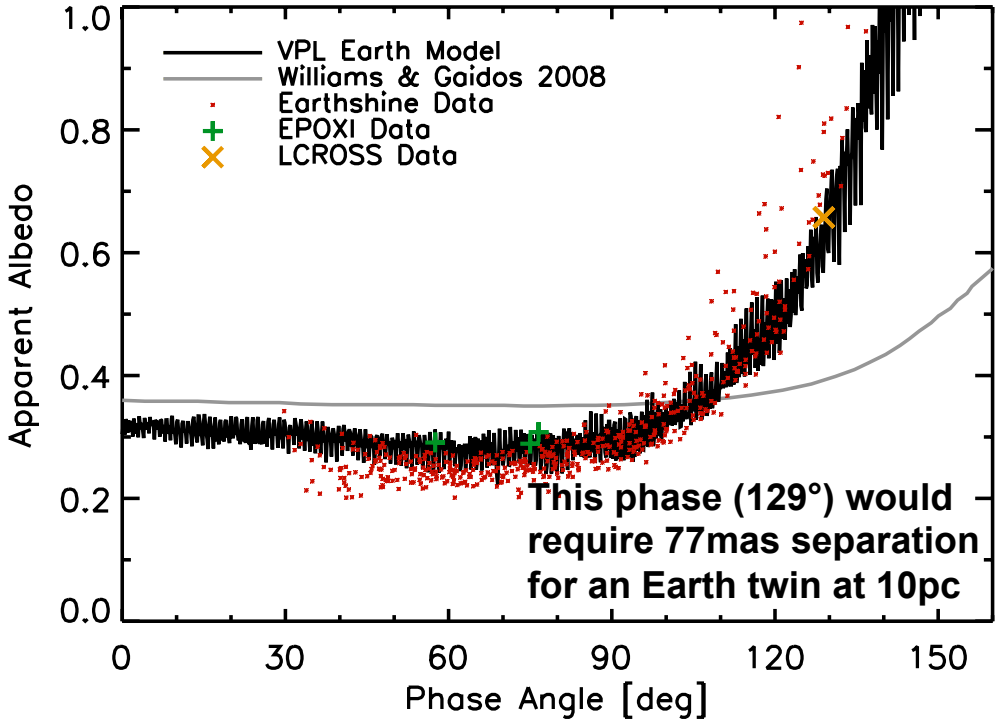




Cowan et al., 2010, Robinson et al., 2011

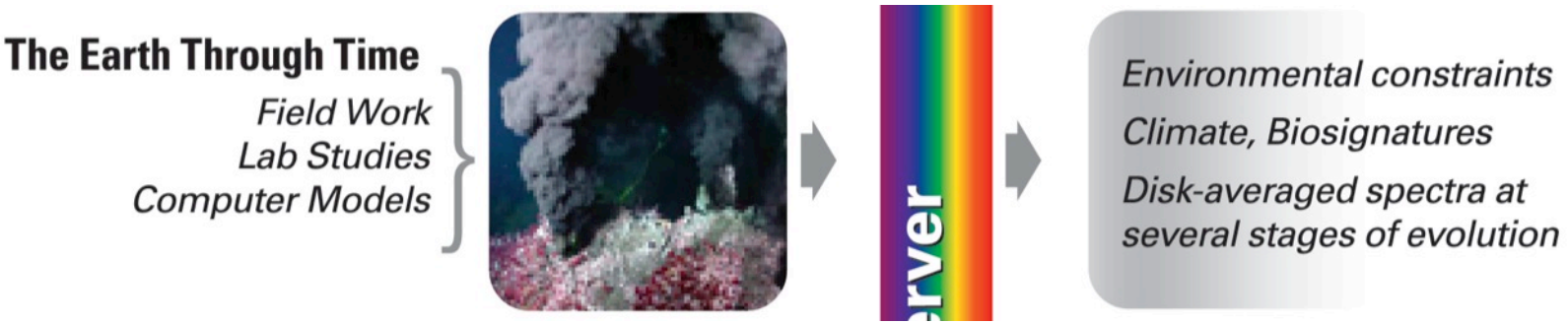






Robinson et al., 2014

- Collaboration with NLSI and LCROSS to validate the Earth model and test the detectability of ocean glint and ozone.



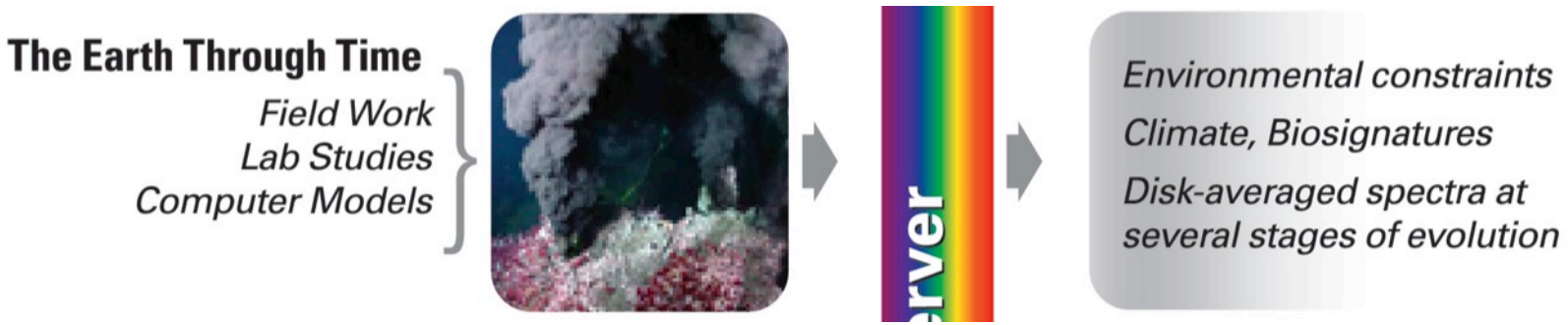
Objective 2: Characterize the Environment, Habitability and Biosignatures of the Earth Through Time.

For several critical periods throughout the Earth's history we will synthesize field, laboratory and modeling efforts to constrain planetary environmental parameters including surface temperature, atmospheric pressure and composition, and to determine biogeochemical cycling and greenhouse effects consistent with these constraints.

Products:

- **improved understanding of the environmental parameters, climate and atmospheric biosignatures for ecosystems and environments dominated by a wide range of different metabolisms.**

Time Peroid / Redox State / Metabolism	Paleoarchean / Reducing / methanogenesis	Mesoarchean - Neoarchean Anoxic / Anoxygenic photosynthesis	Proterozoic/ Oxidized atmosphere, sulfidic oceans / oxygenic photosynthesis	Phanerozoic / Oxidized surface / oxygenic photosynthesis
Parameter				
Nutrient cycling	Catling (M)	Catling (M)	Catling (M), L	Catling (M), L
Surface P	Buick (D), Kasting, Zahnle, Conrad, Bolton, Sleep (M)	Buick (D), Kasting, Zahnle, Conrad, Bolton, Sleep (M)	Buick (D), Kasting, Zahnle, Conrad, Bolton, Sleep (M))	Buick (D), L
Surface T	Data, Models	Data, Models	Data, Models	Literature
Ocean T	Data, Models	Data, Models	Data, Models	Literature
Ocean Composition	Catling (M), Literature	Catling (M), L	Literature	Literature
Atmos. Composition	Zahnle (M), Literature	Zahnle (M), L	Buick (D), Zahnle (M), L	Literature
Redox Proxy	Zahnle, (MD), Literature	Zahnle, (MD), L	Zahnle, (MD), L	Literature
Greenhouse	Kasting, Domagal-Goldman (Models)	Kasting, Domagal-Goldman (M)	Buick (D), Catling, Kasting (M)	Literature
Productivity	Hoehler, Catling, Domagal-Goldman (M), L	Hoehler, Catling, Domagal-Goldman (M), Task D, L	Hoehler, Catling, Domagal-Goldman (M), L	Task D, L
Biosignature	Domagal-Goldman (M)	Domagal-Goldman (M), Task D	Domagal-Goldman (M), L	Task D
Metabolism	Baross (M, D), Domagal-Goldman, Hoeler (M), L	Baross (M, D), Domagal-Goldman, Hoeler (D), Task D, L	Baross (M,D), Task D, L	Task D, L



A meerkat licking Archean raindrop impact craters, the size of which indicates that atmospheric density ~2.7 billion years ago was similar or lower than now (Som et al., 2012)

Objective 3: Develop Interdisciplinary, Multi-Parameter Characterization of Exoplanet Habitability.

Interdisciplinary exploration of the interdependent effects of the Galactic environment, parent star, planetary system environment and planetary characteristics on planetary habitability.

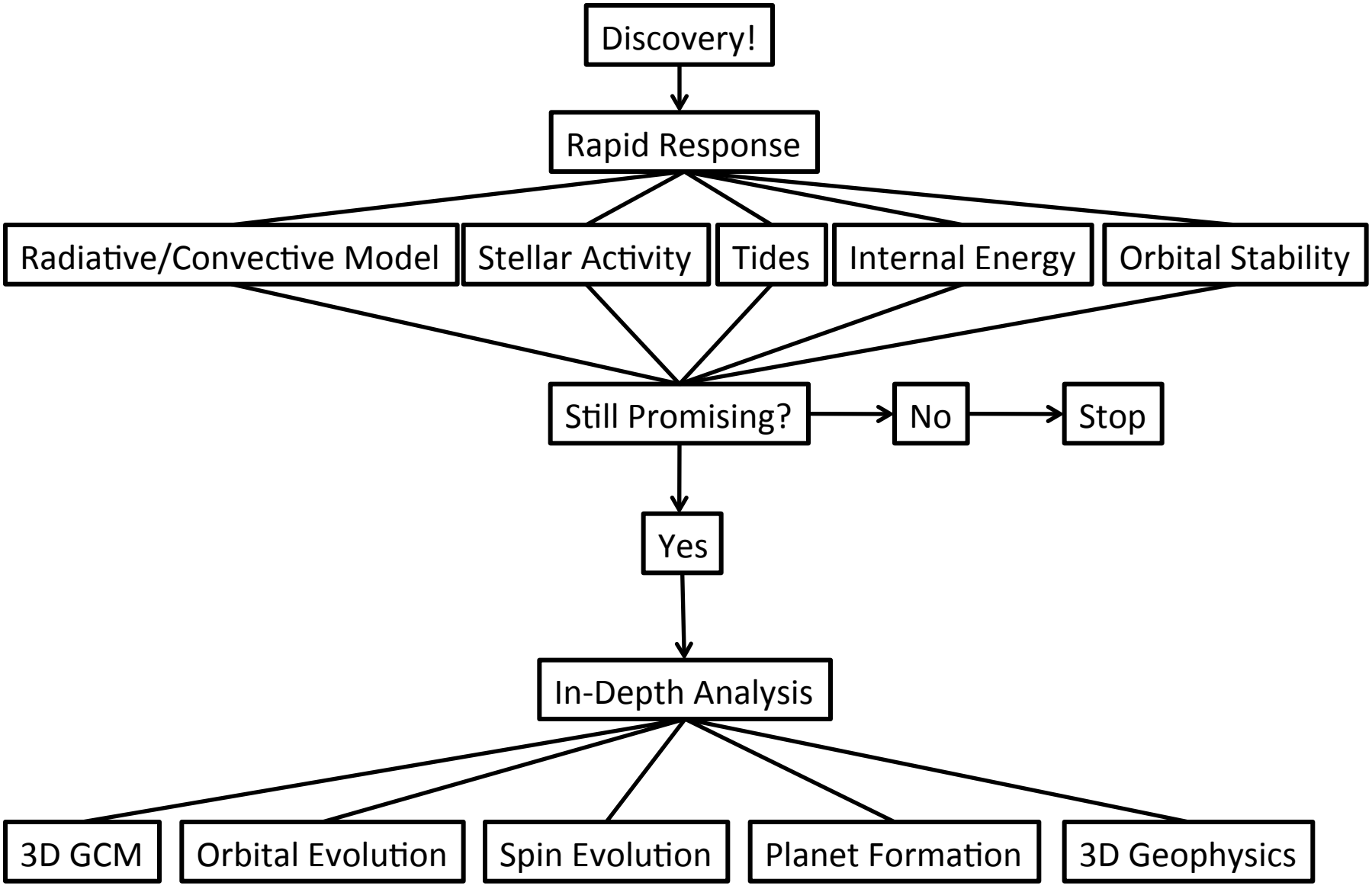
Galactic interactions, stellar radiative and gravitational interactions, stellar activity, limits of the habitable zone using 1-D and 3-D models.

One focus will be on factors affecting M dwarf planets, as these are likely to be the first targets amenable to spectroscopic follow-up.

Products:

- a more complete picture of planetary habitability,
- an enhanced tool box of coupled codes.
- Modeling tools will be used to assess and rank newly discovered planets for likely habitability, and prioritize them for follow-up.

VPLanet


Discovery!
Rapid Response
Radiative/Convective Model
Stellar Activity
Tides
Internal Energy
Orbital Stability
Still Promising?
No
Stop
Yes
In-Depth Analysis
3D GCM
Orbital Evolution
Spin Evolution
Planet Formation
3D Geophysics

The Habitable Planet

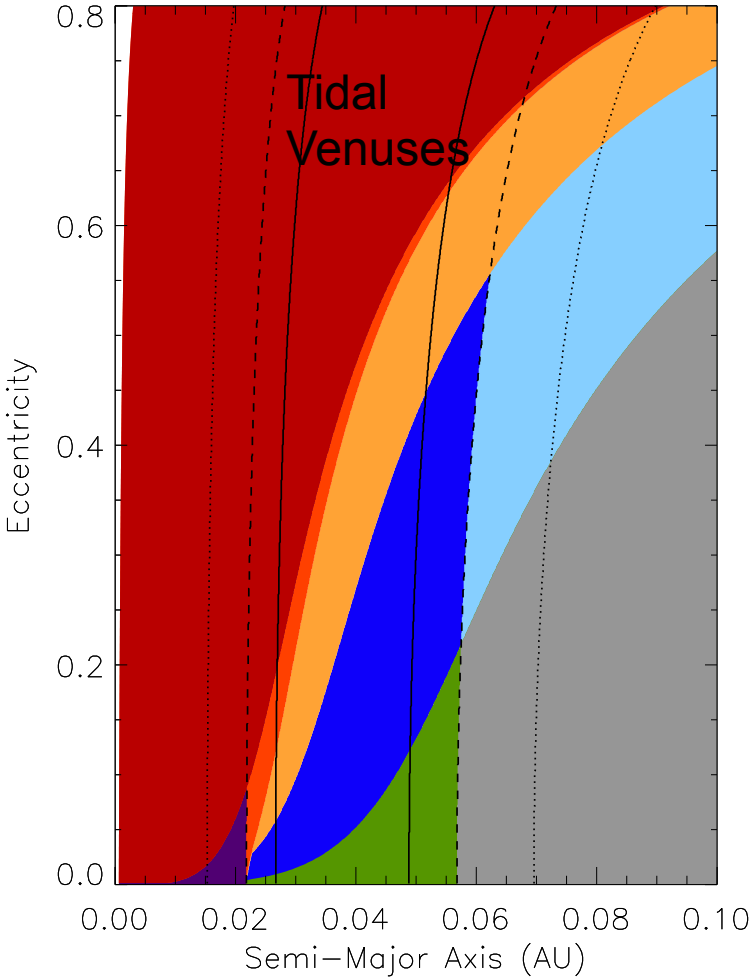
Planet Formation
1-D/3-D Climate/Chemistry
Orbital Dynamics
Stellar Observations

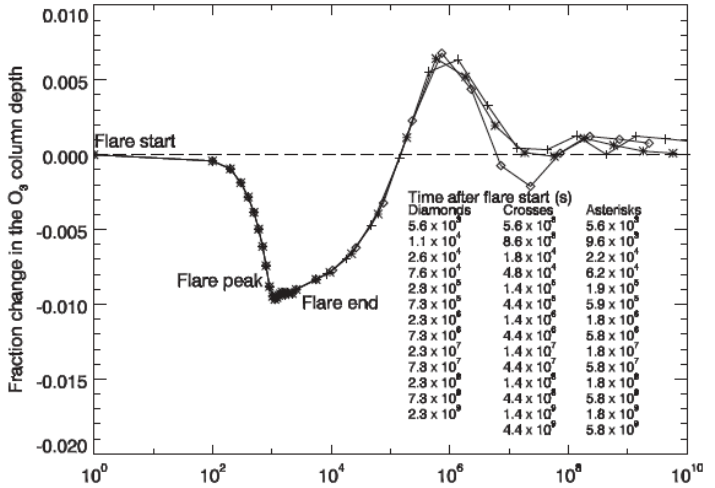
Obs

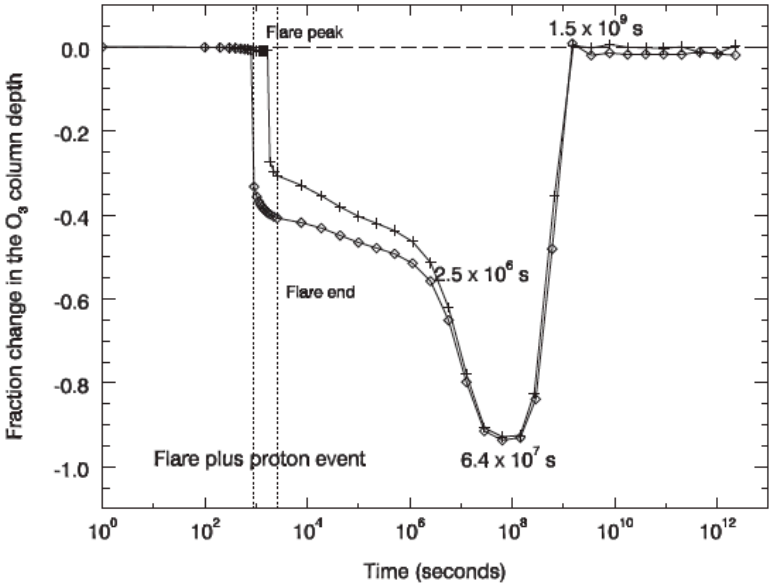
Habitability assessment

Disk-averaged spectra

Climate and limits of the habitable zone for plausible extrasolar planets

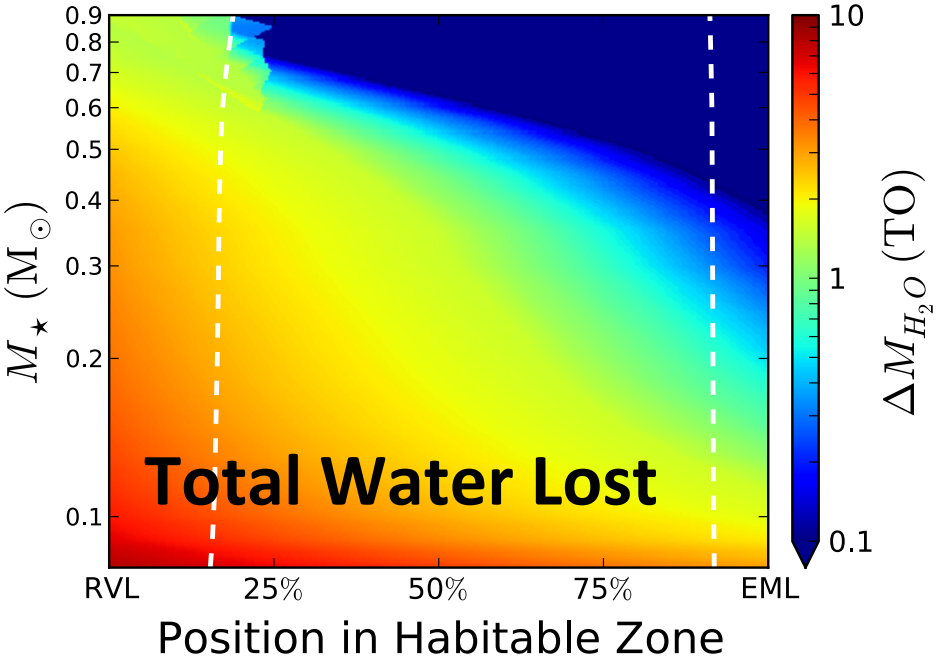






Barnes et al., 2012;
Segura, Walkowicz et al., 2010

O_2 as a Biosignature – Planetary False Positives are Growing…

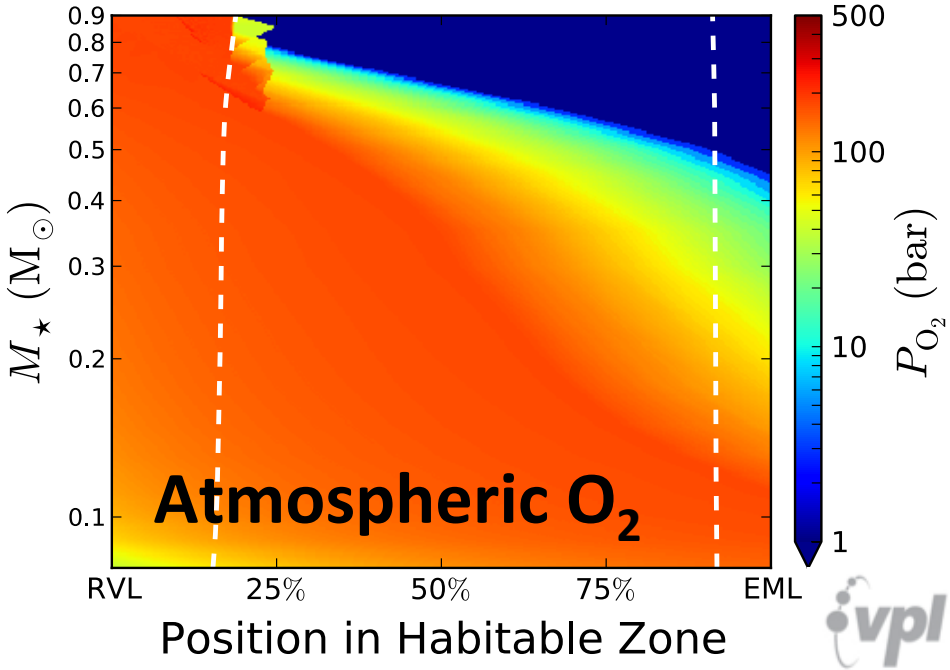


VPL researchers show that terrestrial planets can lose several Earth oceans of water via hydrodynamic escape during the super-luminous PMS phase of M dwarfs.

Luger & Barnes (2014), *in review*

Depending on surface sinks, up to several hundreds of bars of photolytically-produced O_2 can potentially build up in the atmospheres of these planets.

Luger & Barnes (2014), in review



Objective 4: Determine the Impact of Life on Terrestrial Planet Environments and the Generation of Biosignatures.

Use field and laboratory research integrated with coupled chemical, climate and ecosystem models to explore life's co-evolution with its environment, and the limits of photosynthesis.

Biogenic Gases from Anoxygenic Photosynthesis in Microbial Mats

The Long Wavelength Limit of Photosynthesis

Coupled Ecosystem Climate Modeling

Generation of New Biosignatures via Photochemical Modeling

Thermodynamic and Kinetic Disequilibrium Biosignatures.

Products:

- **Identification of new remote-sensing atmospheric and surface biosignatures**
- **Improved understanding of how photosynthesis may adapt to extrasolar light environments.**

The Living Planet

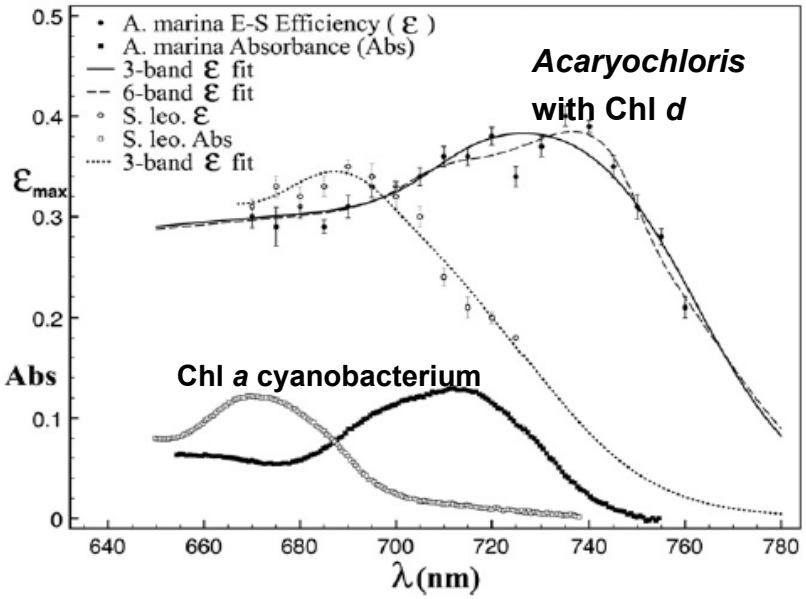
Field Work
Lab Studies
Computer Models

Limits of photosynthesis

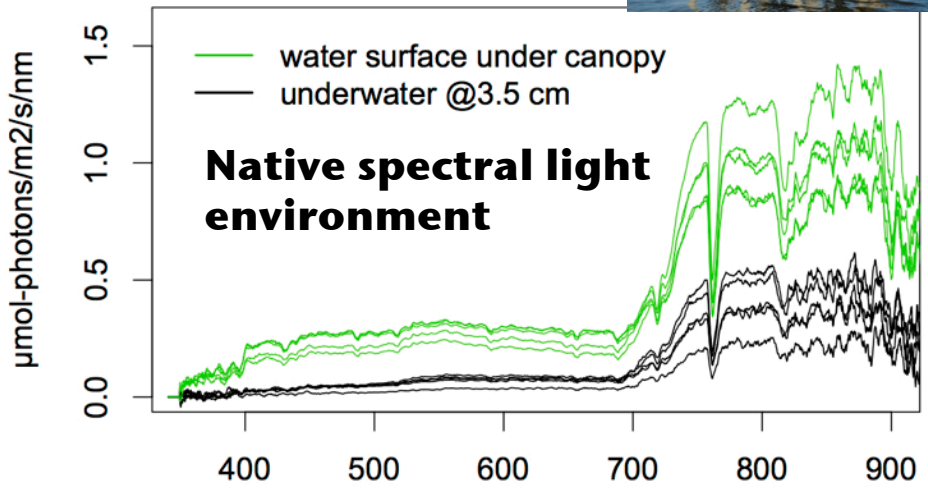
Impact of life on planetary environments

New biosignatures

Cellular & Molecular Biophysics



Mielke et al (2013) BBA, 1827(3):255-265



Kiang et al., in prep

Objective 5: Define Required Measurements and Optimal Retrieval Methods for Exoplanet Characterization Missions.

Use Kepler data of multiplanet systems to search for new, smaller planets and constrain planetary mass.

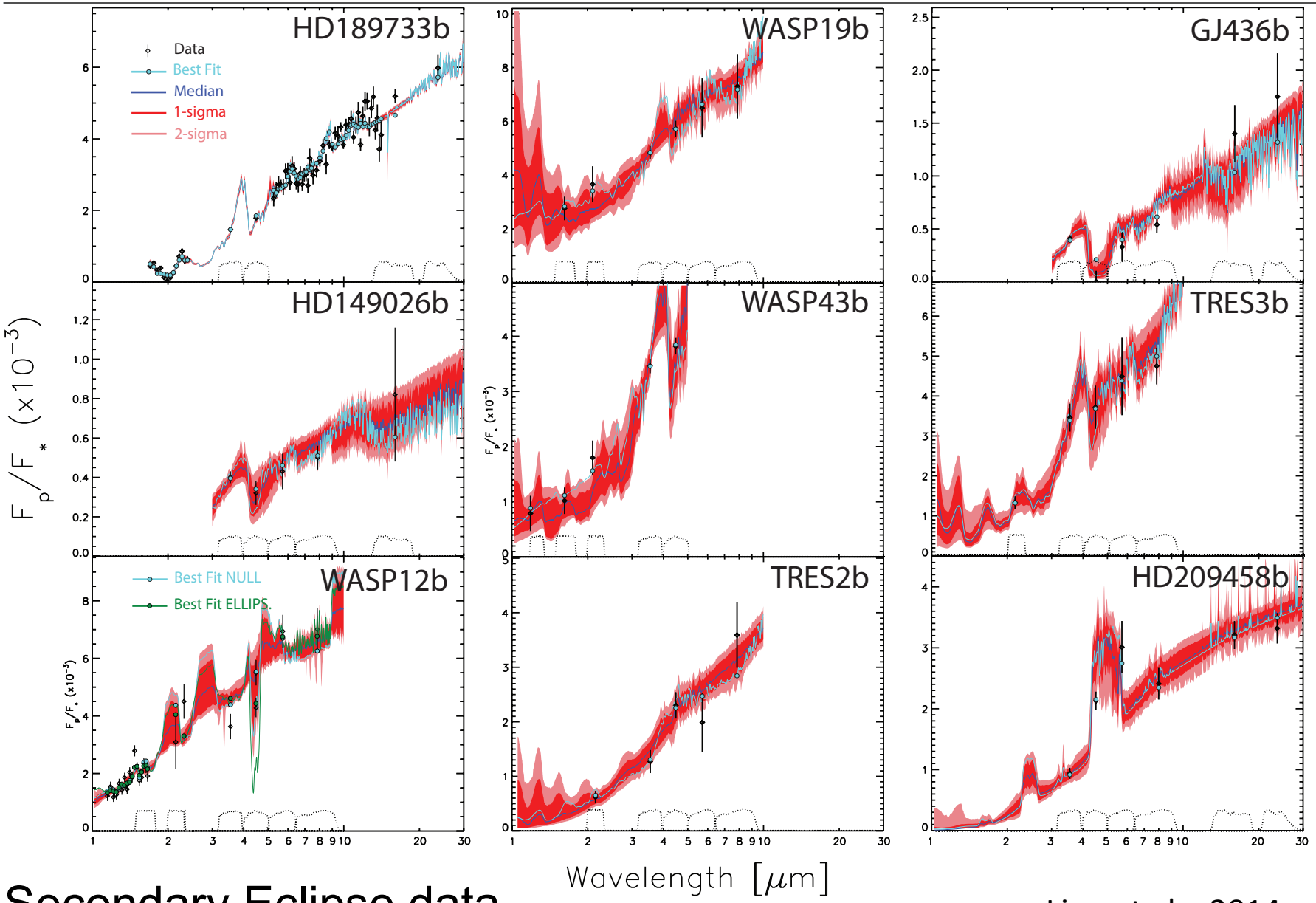
Develop an optimal exoplanet spectral retrieval system for determination of planetary atmospheric and surface properties from exoplanet spectra.

- specifically for exoplanet data
- will incorporate consistency with known data on the planet, and basic physical and chemical constraints on planetary atmospheres.
- Uses existing instrument simulators for JWST, and other exoplanet detection and characterization missions.

Products:

- Assessment of the detectability of signs of habitability and life for the early Earth and exoplanet environments generated by the previous four tasks.

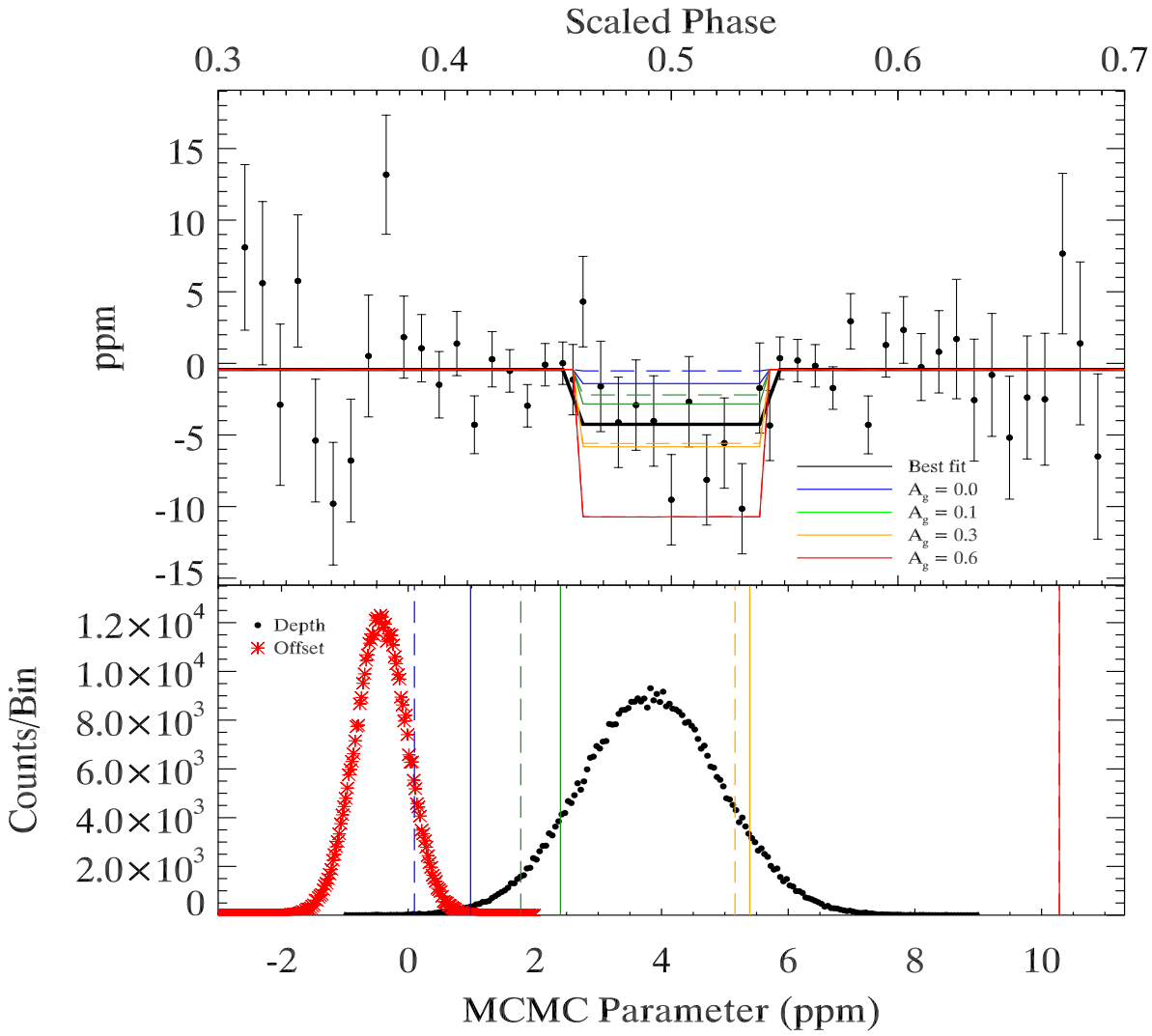
Atmospheric Retrieval Analysis on *Real* Data



Secondary Eclipse data

Line et al., 2014

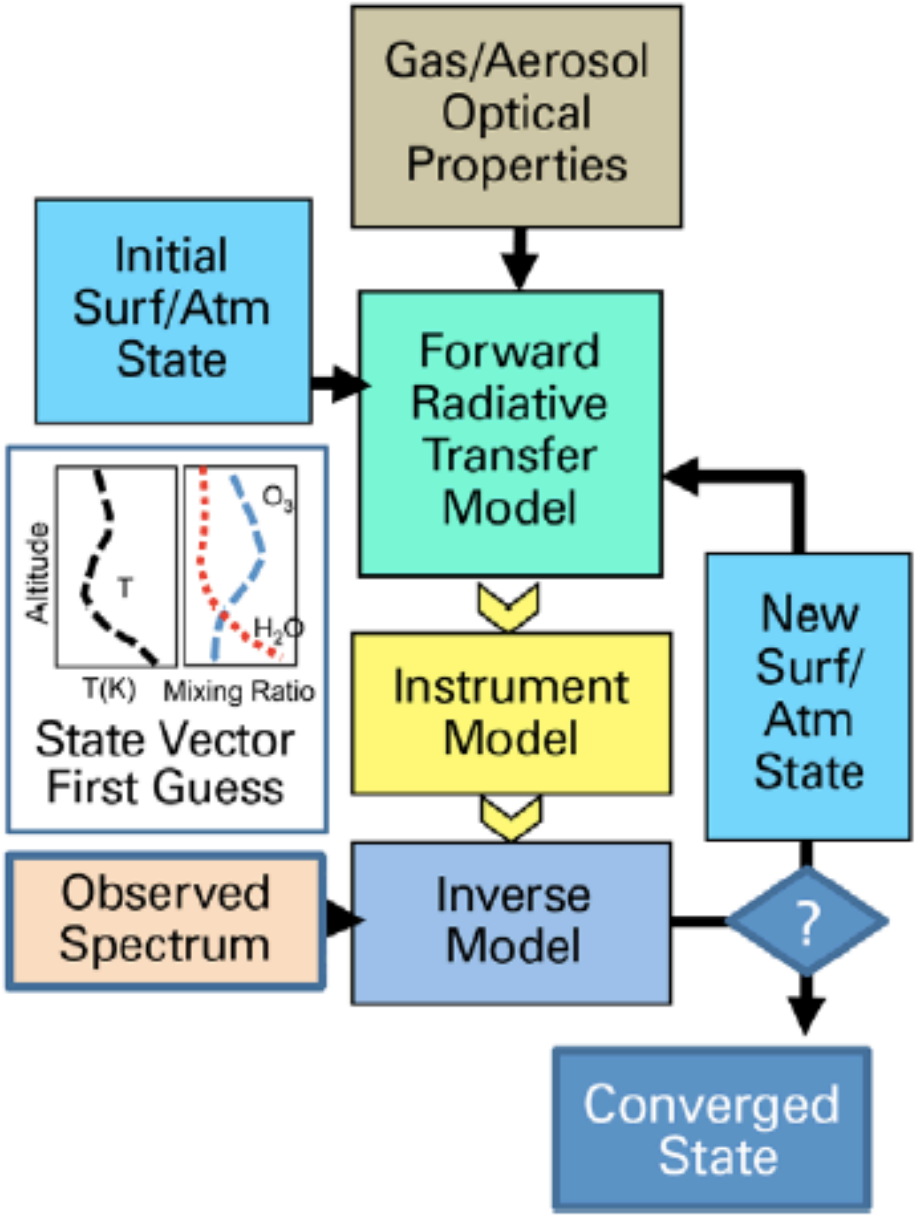
Ensemble Planetary Albedo Determination

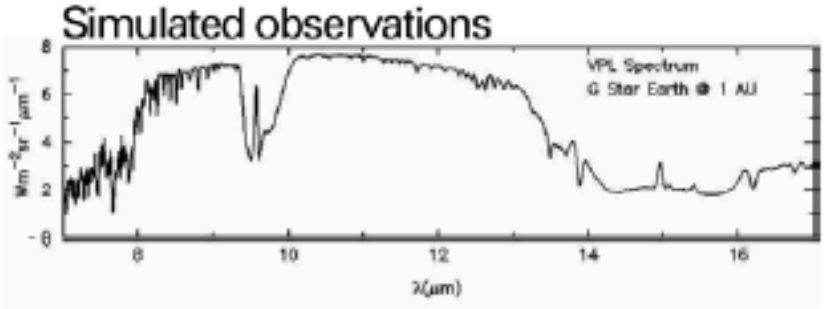


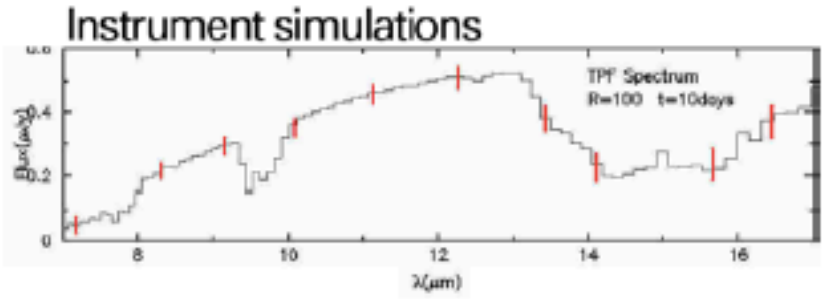
- 5340 total eclipses
- Albedo = 0.22 +/- 0.06 (if no thermal)
- Without Kepler-10b

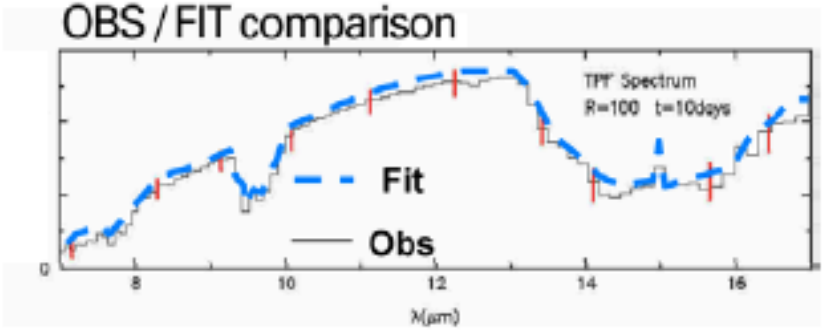
Sheets and Deming, 2014, ApJ, 794, 133S

Atmospheric Retrieval for Terrestrial Exoplanets





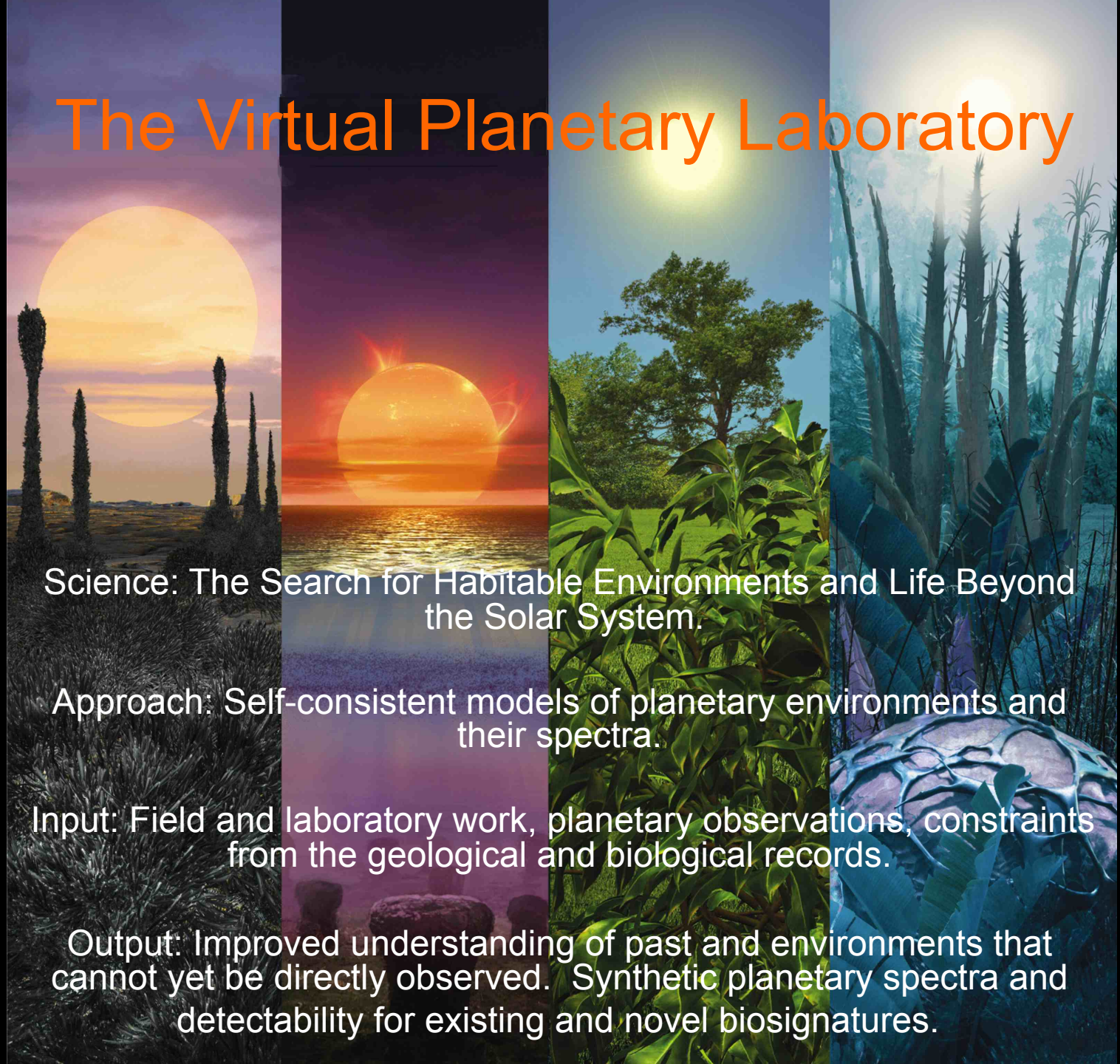




Education and Public Outreach

- Partnership with the Pacific Science Center in Seattle
  - Science on a Sphere
  - Science Communication Fellows
  - Portal to Current Research
  - Science Cafes
- UW Astrobiology Colloquium Series
- Astrobiology 115
  - Expansion of students taught
  - Packaging of course materials for use by other institutions.
- Participation in Joint NAI Efforts.
- UW Dual-Title PhD in Astrobiology.

The Virtual Planetary Laboratory



Science: The Search for Habitable Environments and Life Beyond the Solar System.

Approach: Self-consistent models of planetary environments and their spectra.

Input: Field and laboratory work, planetary observations, constraints from the geological and biological records.

Output: Improved understanding of past and environments that cannot yet be directly observed. Synthetic planetary spectra and detectability for existing and novel biosignatures.